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Radiation Performance of AlGaAs and InGaAs Concentrator Cells and Expected Performance of Cascade Structures

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RADIATION PERFORMANCE OF AlGaAs and InGaAs CONCENTRATOR CELLS

AND EXPECTED PERFORMANCE OF CASCADE STRUCTURES

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SUMMARY

AlGaAs, GaAs, silicon and InGaAs cells have been irradiated with 1 MeV electrons and 37 MeV protons. These cells are candidates for individual cells in a cascade structure. Data is presented for both electron and proton irradiation studies for one sun and a concentration level of 100X AMO. Results of calculations on the radiation resistance of cascade cell structures based on the individual cell data are also presented. Both series connected and separately connected structures are investigated.

INTRODUCTION

For many years, concentrator PV systems have been under strong consideration for use in space. The advantages to concentrator PV include higher cell efficiency, better radiation resistance and a cost effective way of using advanced PV technology such as multi-junction cells. Several optical designs are being studied such as the miniature Cassegrainian system developed by TRW (ref. 1), and the SLATS trough system developed by General Dynamics. Both designs utilize small cells with illuminated areas a fraction of a square centimeter.

One of the concerns about concentrator PV is the effect of particle radiation on the cell performance at concentrated light levels. As part of an ongoing program at NASA Lewis Research Center, we have irradiated several types of concentrator cells with 1 MeV electrons and 37 MeV protons and measured the performance degradation. Results for several GaAs cells were presented at the 18th PVSC (ref. 2). The results presented here are for AlGaAs, GaAs, InGaAs and silicon cells irradiated with 1 MeV electrons to a fluence of $3x10^{15}$ e/cm^2 and identical cells except InGaAs irradiated with 37 MeV protons. Results are also given for the calculated performance of multi-junction cells under both 1 MeV electron and 37 MeV proton irradiation.

CELL DESCRIPTION

The III-V cells used in these irradiations were made by Varian. The bandgaps were 1.72 eV for the AlGaAs cells, 1.43 eV for the GaAs cells, and 1.1 eV for the InGaAs cells. The cells are all OM-VPE grown with an appropriate window. The AlGaAs cells were n/p while the GaAs and InGaAs cells were p/n. The GaAs cells had a junction depth of 0.5 μm and the AlGaAs and InGaAs were about the same. The silicon cells are 2 Ω-cm n/p cells with a junction depth of 0.2 μm. They were supplied by ASEC. All the cells are small area concentrator cells. There were a minimum number of cells available for this effort and some care should be taken in analyzing the data because of the small sample size. A summary of cell bandgaps, illuminated diameters, and number of cells irradiated is given in table I.

EXPERIMENTAL DESCRIPTION

All of the small area concentrator cells were individually mounted in separate cell holders. For the silicon, GaAs and AlGaAs cells, the holders consisted of a small bottom metal base and a washer-like metal top with a beveled hole slightly larger than the illuminated area of the cell. These two pieces supply both a permanent support for the cell and an area for the four-wire electrical attachment. There was no soldering or welding of any contact to these cell. The InGaAs cells were mounted in holders by Varian with top contacts attached directly to the outer busbar. The cells remained in their holders throughout all electron irradiations and performance measurements. For the proton irradiations, the GaAs cells remained in their holders while the silicon and AlGaAs cells were irradiated outside the holders and remounted for measurements. There were no cover glasses attached to the cells, nor was there any shielding by optical elements during the irradiations.

Electron irradiations using 1 MeV electrons were performed at the Naval Research Laboratory Van de Graff generator. The cells were irradiated to a total fluence of 3×10^{15} electrons/cm^2, with performance measurements made at several intermediate fluence levels. Proton irradiations using 37 MeV protons were made at the NASA Lewis cyclotron at fluences up to 3×10^{12} protons/cm^2. The performance measurements consisted of the following:

1. I-V data at 25 °C and 1 AMO using an X-25 xenon solar simulator and a reference cell.

2. I-V data at 25 °C at several concentrations up to 100X AMO and above using a pulsed xenon solar simulator and the linear assumption between irradiance and short circuit current.

3. Short circuit current data at one fixed concentration at both 25 °C and 80 °C in order to set the current scale at the elevated temperature.

4. I-V data at 80 °C at several concentrations as in step 2 above.

During I-V measurements the cells in their holders are mounted to a temperature controlled block. The concentration level on the cell is varied by a combination of changing the distance from the light source and the use of a fresnel lens. Since the duration of the light pulse from the flash simulator is just 2 ms, there is no heating effect from the concentrated light. The elapsed time at 80 °C was about 30 min for each cell. Several repeat measurements were made at 1 sun and 25 °C after the elevated temperature measurements, in order to determine if any annealing had taken place.

RESULTS AND DISCUSSION

Table II shows the average starting electrical parameters (before irradiations) for the four different cell types. The data are for 25 °C and

100X AMO and include cells irradiated by both electrons and protons. All the cells showed excellent efficiencies at 100X, especially the GaAs cells which averaged 21.3 percent for the six cells irradiated.

Tables III to V show the ratios of short circuit current, open circuit voltage, fill factor and maximum power after irradiation to the unirradiated values for several fluence levels at three different measurement conditions for 1 MeV electrons and 37 MeV protons. Data are given for 25 °C 1 sun, as well as 25 and 80 °C at 100X concentration. The ratios for short-circuit current at 25 °C are the same for both solar irradiation levels due to the linear current-irradiance assumption.

Figure 1 shows plots of normalized maximum power as a function of 1 MeV electron irradiation for the four cell types at 25 °C and 100X AMO. The InGaAs and silicon cells show more degradation at the higher fluences than the AlGaAs or GaAs cells. It is difficult to draw conclusions from these curves because they are based on a small number of cells (2 each of AlGaAs and InGaAs and 4 each of silicon and GaAs). However there may be a trend of more radiation resistance with increasing bandgap. If so, this could be beneficial for multijunction cells where the higher bandgap cells produce more of the power. Figure 2 shows normalized maximum power versus the 37 MeV proton fluence also at 25 °C and 100X. Again, the silicon cells are degraded much more than the AlGaAs or GaAs. There were no proton irradiations for InGaAs cells.

The data presented in figures 1 and 2 are for results at 25 °C and 100X. However we do have data at 1 sun as well as 80 °C at 100X. The degradation is not the same at all three measurement conditions, as the data in tables III, IV and V show. An example is given in figure 3 which shows the normalized P_{max} versus electron fluence for AlGaAs at the three different conditions. The spread in degradation at 100X between 25 and 80 °C is slightly larger than typical, however it should not change any conclusions drawn from the data. There are some larger differences between the one sun data and the 100X data at 25 °C (note the silicon cells under proton irradiation), however these are small area cells designed to operate at concentration. There could be some leakage currents which are affected by radiation. They would be much less significant at the higher current densities at 100X concentration.

For the AlGaAs, InGaAs and silicon cells, the major contribution to power degradation was the current loss. This was for both 1 MeV electrons and 37 MeV protons, at both one sun and 100X AMO. For the GaAs cells, both the current and voltage contributed to the power degradation except for the 1 sun -- electron case which was current dominated. In all cases the fill factor usually had very little degradation.

During the measurement portions of this work, we took some temperature dependence data at 100X. Figure 4 shows short-circuit current at 100X for InGaAs versus temperature for several 1 MeV electron fluence levels. The important factor to note is the slope of the curves increases with increasing electron fluence. At the unirradiated level the Isc temperature coefficient is 0.40 A/K, while at 3×10^{15} it is 1.67 A/K. This is an an increase of a factor of four while the actual current is about half the unirradiated value. For the silicon cells, the temperature coefficient approximately doubles for both electron and proton irradiations, while the GaAs and AlGaAs Isc coefficients are nearly constant. This effect has been noted in silicon before (ref. 3) and it was suggested that the temperature dependence of the minority carrier lifetime was radiation dependent. The present data indicate that the same effect occurs with the InGaAs cells.

During the course of the measurements, each cell was heated to 80 °C for about 30 min. For several cells, repeat data points were taken at 25 °C afterwards to look for any annealing effects. In all cases there was no annealing due to the 30 min spent at 80 °C.

All of the results presented have been for individual cells, and are actual measured data. Since we have data for cells of different bandgaps, we can calculate the performance of multi-junction cells under both 1 MeV electron and 37 MeV proton irradiations. Both the AlGaAs/InGaAs pair and the AlGaAs/silicon pair are good candidates for this calculation since the bandgaps, 1.72 and 1.1 eV, are near the ideal pair for optimum multi-junction performance. When the AlGaAs cell is used as a top cell, the bottom cell (InGaAs or silicon) is filtered by the AlGaAs cell and has less sunlight incident upon it. Since the bandgaps are near optimum for a series connected multi-junction cell, we reduced the irradiance on the bottom cell until the currents matched at the unirradiated fluence level. With 100X concentration on the AlGaAs cell, we had about 56X on the InGaAs cell and 51X on the silicon cell. Since data was taken at several concentration levels at 25 °C at each fluence, we can readily obtain data for the bottom cells at reduced concentration for all fluence levels.

There are two cases of multi-junction cells of interest. One is the separately connected or 4-terminal structure and the second is the series connected structure. In the separately connected case, the performance of the multi-junction cell can be calculated just by adding the maximum powers of the individual cells. The series connected structure requires adding actual I-V curves in series. In this case, if the currents are mismatched, the output power will be less than the simple sum of the individual cell powers.

The diode equation was used to obtain I-V curves of individual cells for the series connected case. The light generated current was set to the desired short-circuit current while the coefficients of the injection term and space-charge recombination term were varied to match Voc and fill factor. A series resistance of less than 0.05 Ω/cm^2 was used. We were then able to calculate an entire I-V curve to match any set of parameters. In order to add two I-V curves with different currents, a reverse characteristic for the lower current curve is required. For this work we assumed the curves broke down at a voltage between -2 and -3 V.

Figure 5 shows the calculated degradation in P_{max} for both the series connected and separately connected (stack) multi-junction cells under 1 MeV electron irradiation. The operating conditions are 25 °C and 100X AM0 incident on the top cell. We also show the individual curves for the top AlGaAs and the "filtered" bottom InGaAs cells. All curves are normalized to the unirradiated cascade P_{max}. The curves for the individual cells indicate the relative importance of the top and bottom cell with the top cell producing about 65 percent of the total cascade output power. For the cascade structures, note that for very low fluences, the difference between series and separate connections is quite small. However as the currents of the two cells diverge at higher fluence levels, the series connected case falls to a point where the multi-junction cell delivers less power than a bare AlGaAs cell would. This is due to the limiting action of the large current mismatch between the two individual cells

Figures 6 and 7 show similar results for the AlGaAs/silicon cascade cell. Fig. 6 is for 1 MeV electrons and figure 7 is for 37 MeV protons. The trends are the same for these two cases as they are for the AlGaAs/InGaAs pair of figure 5.

The above results indicate that for high radiation missions, it will probably be necessary to use the separately connected version of multi-junction cells due to the problems created by current mismatch. For shorter missions in a low radiation orbit, the series connected version would perform just as well as the 4-terminal version. It must be noted that this work is based on 1 MeV electron and 37 MeV proton irradiations only on a small number of cells. Further work is required to more completely investigate the radiation performance of multi-junction cells.

CONCLUSIONS

One MeV electron and 37 MeV proton irradiations were made on four types of small concentrator solar cells. The major results were:

1. AlGaAs and GaAs cells were much more radiation resistant than InGaAs or silicon cells.

2. For cascade cells, the series connected structure degrades much more quickly than the separately connected structure due to current mismatches.

3. The temperature coefficient for InGaAs Isc increases with increasing electron fluence probably due to radiation effects on the minority carrier lifetime temperature dependence.

ACKNOWLEDGMENT

The electron irradiation facilities at Naval Research Laboratory were made available through the cooperation of Richard Statler and Robert Farr.

REFERENCES

1. R.E. Patterson, "Preliminary Concept of a 100-Kilowatt Miniaturized Cassegrainian Concentrator Solar Array", in Space Photovoltaic Research and Technology 1983, NASA CP-2314, 1983, pp. 157-162.

2. H.B. Curtis and C.K. Swartz, "Performance of GaAs and Silicon Concentrator Cells Under 1 MeV Electron Irradiation", in Eighteenth IEEE Photovoltaic Specialists Conference, Piscataway, NJ: IEEE, 1985, pp. 356-361.

3. The electron irradiation facilities at NRL were made available through the cooperation of Richard Statler and Robert Farr.

4. D.J. Curtin and R.W. Cool, "Qualification Testing of Laboratory Produced Violet Solar Cells", in Tenth IEEE Photovoltaic Specialists Conference, Piscataway, NJ: IEEE, 1973, pp. 139-152.

Table I. - DESCRIPTION OF CELLS

Cell type	Bandgap, eV	Diam., mm	Cells irradiated	
			Electrons	Protons
AlGaAs	1.72	6.3	2	2
GaAs	1.43	4.0	4	2
InGaAs	1.1	6.3	2	0
Silicon	1.1	4.0	4	2

Table II. - INITIAL I-V DATA

[100X AMO - 25 °C.]

	AlGaAs	GaAs	InGaAs	Silicon
Isc/cm^2, A	1.961	3.174	3.579	3.834
Voc, V	1.367	1.139	.859	.724
Fill	.835	.799	.794	.800
Efficiency, percent	16.5	21.3	18.1	16.4

Table III. - RATIOS OF IRRADIATED TO INITIAL VALUES AT 25 °C AND 1X

(a) 1 MeV electrons

Fluence, e/cm^2	Isc	Voc	Fill	P_{max}
AlGaAs				
1x10^{13}	1.002	0.998	1.005	1.007
3x10^{13}	.998	.999	1.008	1.007
1x10^{14}	.993	.997	1.003	.993
3x10^{14}	.968	.987	1.003	.959
1x10^{15}	.909	.967	.986	.868
3x10^{15}	.821	.938	.971	.747
GaAs				
1x10^{13}	0.989	1.002	1.000	0.991
3x10^{13}	.978	.994	1.009	.981
1x10^{14}	.965	.993	1.007	.965
3x10^{14}	.927	.977	1.011	.923
1x10^{15}	.875	.957	1.020	.860
3x10^{15}	.776	.928	1.036	.750
InGaAs				
1x10^{13}	0.974	1.006	0.995	0.976
3x10^{13}	.973	.999	.996	.969
1x10^{14}	.942	.989	.995	.929
3x10^{14}	.879	.980	.998	.860
1x10^{15}	.687	.929	.995	.637
3x10^{15}	.460	.857	.989	.393
Silicon				
1x10^{13}	0.982	0.997	0.999	0.979
3x10^{13}	.946	.992	.993	.932
1x10^{14}	.876	.974	1.002	.865
3x10^{14}	.787	.965	.996	.756
1x10^{15}	.674	.940	1.004	.636
3x10^{15}	.547	.900	.993	.489

TABLE III. - Continued.

(b) 37 MeV protons

Fluence, p/cm^2	Isc	Voc	Fill	P_{max}
AlGaAs				
7.6x10^{10}	0.983	0.988	1.007	0.979
2.5x10^{11}	.968	.983	.994	.946
6.2x10^{11}	.953	.976	.988	.920
2.8x10^{12}	.915	.959	.986	.865
GaAs				
7.6x10^{10}	0.987	0.999	0.995	0.982
2.5x10^{11}	.972	.988	1.005	.966
6.5x10^{11}	.955	.970	1.002	.929
3.0x10^{12}	.924	.934	1.021	.882
Silicon				
7.6x10^{10}	0.869	0.954	0.912	0.758
2.5x10^{11}	.759	.929	.875	.617
6.2x10^{11}	.711	.895	.837	.535
2.8x10^{12}	.603	.863	.827	.431

TABLE IV. - RATIOS OF IRRADIATED TO INITIAL VALUES AT 25 °C AND 100X.

(a) 1 MeV electrons

Fluence, e/cm^2	Isc	Voc	Fill	P_{max}
AlGaAs				
$1x10^{13}$	1.002	0.987	0.990	0.979
$3x10^{13}$	.998	.988	.977	.966
$1x10^{14}$	.993	.983	.975	.953
$3x10^{14}$	.968	.979	.963	.913
$1x10^{15}$	.909	.963	.969	.849
$3x10^{15}$	.821	.948	.938	.730
GaAs				
$1x10^{13}$	0.989	0.991	1.010	0.989
$3x10^{13}$	.978	.975	1.029	.978
$1x10^{14}$	.965	.954	1.030	.947
$3x10^{14}$	.927	.925	1.027	.881
$1x10^{15}$	.875	.893	1.033	.807
$3x10^{15}$	.776	.859	1.029	.687
InGaAs				
$1x10^{13}$	0.974	0.996	0.995	0.963
$3x10^{13}$	.973	.998	.997	.968
$1x10^{14}$	.942	.988	.997	.926
$3x10^{14}$	.879	.971	.994	.847
$1x10^{15}$	.687	.933	.975	.623
$3x10^{15}$	.460	.889	.953	.389
Silicon				
$1x10^{13}$	0.982	1.001	0.999	0.990
$3x10^{13}$	.946	.982	1.006	.940
$1x10^{14}$	.876	.980	.998	.861
$3x10^{14}$	.787	.970	1.008	.773
$1x10^{15}$	.674	.933	.996	.630
$3x10^{15}$	.547	.910	.995	.497

Table V. - RATIOS OF IRRADIATED TO INITIAL VALUES AT 80 °C AND 100X.

(a) 1 MeV electrons

Fluence, e/cm^2	Isc	Voc	Fill	P_{max}
AlGaAs				
$1x10^{13}$	1.004	0.992	0.991	0.991
$3x10^{13}$	.996	.994	.988	.982
$1x10^{14}$	.998	.990	.983	.972
$3x10^{14}$	.977	.983	.979	.943
$1x10^{15}$	.926	.967	.970	.871
$3x10^{15}$	.839	.943	.968	.767
GaAs				
$1x10^{13}$	0.988	0.992	0.999	0.980
$3x10^{13}$	.980	.971	1.015	.966
$1x10^{14}$	.965	.947	1.024	.939
$3x10^{14}$	.925	.916	1.036	.871
$1x10^{15}$	.872	.879	1.025	.786
$3x10^{15}$	.779	.840	1.020	.670
InGaAs				
$1x10^{13}$	0.977	0.999	0.986	0.963
$3x10^{13}$	.976	.998	.986	.963
$1x10^{14}$	.951	.995	.990	.939
$3x10^{14}$	.899	.981	.985	.870
$1x10^{15}$	.748	.922	.968	.666
$3x10^{15}$	.527	.884	.946	.441
Silicon				
$1x10^{13}$	0.989	1.012	0.997	0.997
$3x10^{13}$	.959	.988	1.001	.945
$1x10^{14}$	.891	.981	.991	.865
$3x10^{14}$	.802	.964	1.003	.774
$1x10^{15}$	.708	.924	.987	.645
$3x10^{15}$	.579	.886	.990	.507

TABLE V. - Concluded.

(b) 37 MeV protons

Fluence, p/cm^2	Isc	Voc	Fill	P_{max}
AlGaAs				
$7.6x10^{10}$	0.980	0.998	0.994	0.973
$2.5x10^{11}$	.968	.994	.982	.945
$6.2x10^{11}$	.950	.988	.992	.934
$2.8x10^{12}$	.910	.977	.976	.868
Gas				
$7.6x10^{10}$	0.990	0.988	1.003	0.981
$2.5x10^{11}$	.973	.970	.988	.933
$6.5x10^{11}$	.954	.959	.986	.902
$3.0x10^{12}$	.919	.920	.967	.816
Silicon				
$7.6x10^{10}$	0.894	0.993	1.001	0.888
$2.5x10^{11}$	.796	.994	.998	.790
$6.2x10^{11}$	.756	.952	.992	.715
$2.8x10^{12}$	.662	.920	.997	.606

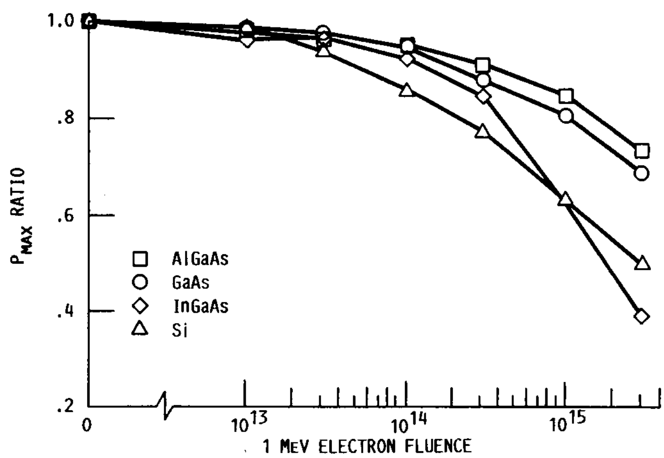

FIGURE 1. - NORMALIZED MAXIMUM POWER FOR AlGaAs, GaAs, SILICON, AND InGaAs CELLS VERSUS 1 MEV ELECTRON FLUENCE. 25 °C - 100X AMO.

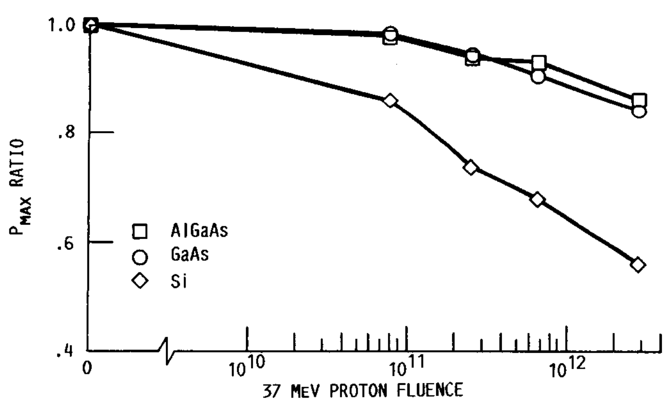

FIGURE 2. - NORMALIZED MAXIMUM POWER FOR AlGaAs, GaAs, AND SILICON CELLS VERSUS 37 MEV PROTON FLUENCE. 25 °C - 100X AMO.

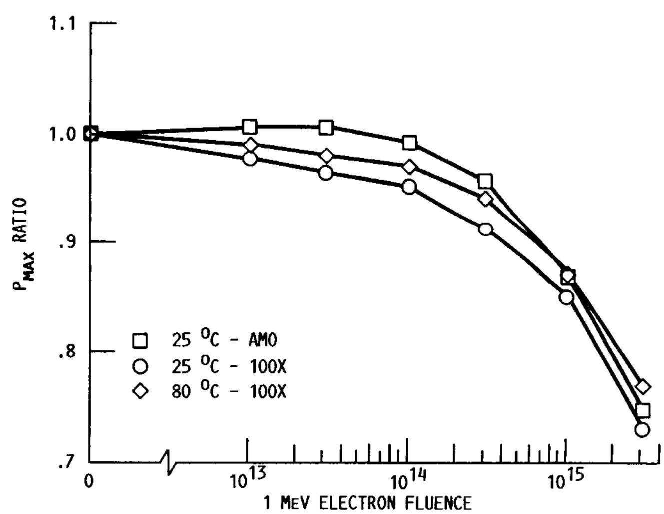

FIGURE 3. - NORMALIZED MAXIMUM POWER FOR AlGaAs CELLS VERSUS 1 MEV ELECTRON FLUENCE FOR THREE MEASUREMENT CONDITIONS.

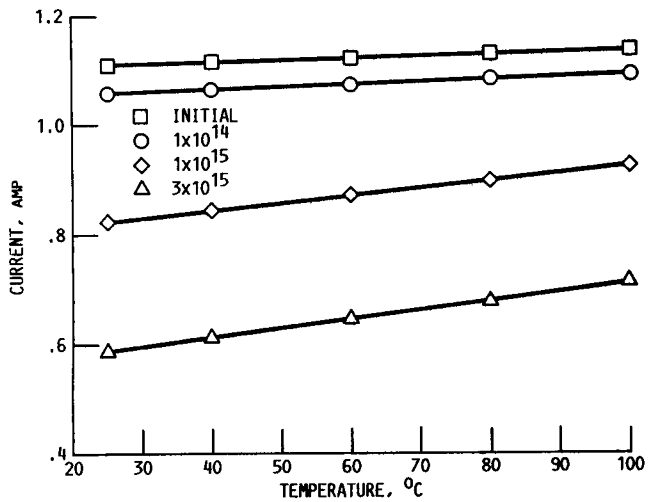

FIGURE 4. - SHORT-CIRCUIT CURRENT FOR InGaAs CELLS AT 100X AM0 VERSUS TEMPERATURE FOR DIFFERENT 1 MeV ELECTRON FLUENCES.

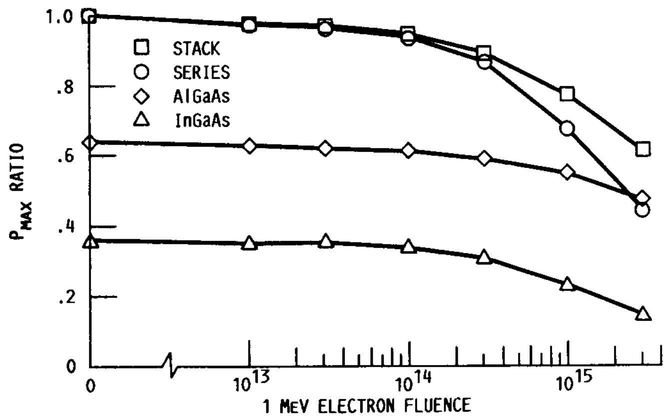

FIGURE 5. - NORMALIZED P_{MAX} VERSUS 1 MeV ELECTRON FLUENCE FOR AlGaAs/InGaAs CASCADE CELLS AND TOP AND BOTTOM COMPONENT CELLS.

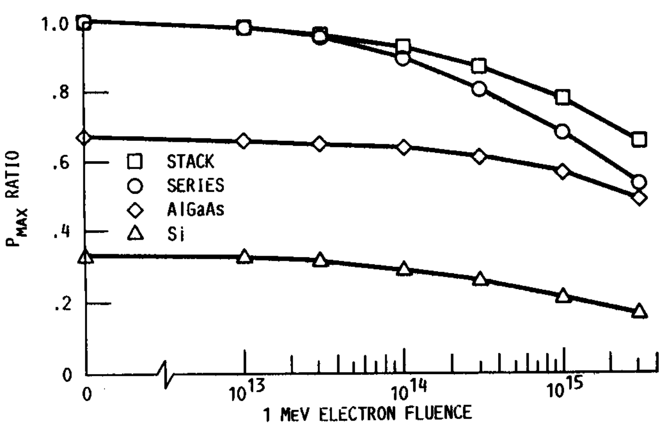

FIGURE 6. - NORMALIZED P_{MAX} VERSUS 1 MeV ELECTRON FLUENCE FOR AlGaAs/SILICON CASCADE CELLS AND TOP AND BOTTOM COMPONENT CELLS.

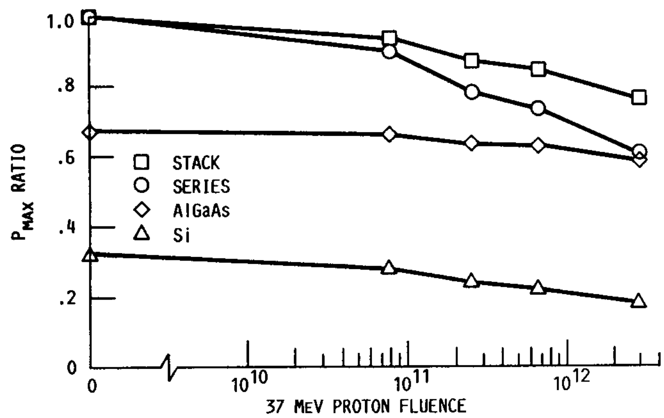

FIGURE 7. - NORMALIZED P_{MAX} VERSUS 37 MeV PROTON FLUENCE FOR AlGaAs/SILICON CASCADE CELLS AND TOP AND BOTTOM COMPONET CELLS.

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16. Abstract

AlGaAs, GaAs, silicon and InGaAs cells have been irradiated with 1 MeV electrons and 37 MeV protons. These cells are candidates for individual cells in a cascade structure. Data is presented for both electron and proton irradiation studies for one sun and a concentration level of 100X AMO. Results of calculations on the radiation resistance of cascade cell structures based on the individual cell data are also presented. Both series connected and separately connected structures are investigated.

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